Convergence in U.S. TFP Growth for Agriculture: Implications of Interstate Research Spillovers for Funding Agricultural Research

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August, 1998
Staff Paper #305

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Abstract

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This paper examines state agricultural total factor productivity (TFP) data, 1950-1982, for evidence of convergence, i.e., TFP growth rates of the future are inversely related to the TFP level at the starting data. After finding evidence of convergence, the paper examines the contributions of public and private R&D to convergence and presents implications for a more efficient organization of public agricultural research. For example, we find that increasing a states own investment in public agricultural research reduces the rate of TFP convergence but larger public investments in surrounding areas that potentially spillin increase the rate of convergence. Also, the results imply that the average rate of convergence in our best fitting model is about 10 percent per year. The finding of strong positive interstate spillover effects of public agricultural research suggests incentives should be considered for stronger cooperation across states on agricultural research funding and new political jurisdictions for financing public agricultural research.

Key words: convergence, total factor productivity, states, spillins, growth, public research, agriculture

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July 26, 1998

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In the United States, the R&D system for agriculture is one of shared financing and performance. The federal government provides about 24 percent of all agricultural research funds, while state governments provide 16 percent and the private sector 60 percent. In contrast, federal agencies actually perform about 15 percent of the research, compared to 31 percent being carried out by state agencies and 54 percent by private businesses (Huffman and Just 1997). With the 1996 agreement between Congress and the President to balance the federal budget by 2002, federal agricultural research and other expenditures are getting close scrutiny. As the federal government shifts greater responsibility to the states for carrying out programs, many state governments are also scrutinizing expenditures. Agricultural research administrators see potential changes and are weighing opportunities and options for future funding.

The advances in knowledge or innovations resulting from public agricultural research may be a local/state, regional, national, or international public good. When knowledge is nonrival and nonexcludable, a pure or international public good is created. The benefits from research conducted in one location become fully available across all regions and countries. In many cases, knowledge is nonrival but partially excludable. Knowledge is an impure public good where the benefits of research conducted in one location become imperfectly available to other locations, or interregional spillover effects are partial (Cornes and Sandler 1996; Evenson 1989). The private-good component of research can only be obtained by undertaking research locally. It cannot be obtained by free-riding on the R&D efforts of other locations.

Recent efforts to understand economic growth have focused on the tendency for growth rates to converge or diverge across regions. Papers by Barro and Sala-i-Martin 1992 and

Baumol, Blackman, and Wolff 1989 focused on unconditional convergence but papers by Grossman and Helpman 1990, Mankiw, Romer, and Weil 1992, and Park, 1995, 1996 have focused on factors that might cause divergence, e.g., human capital and R&D investments. Under these models, the percentage change in output (per capita) is modeled as a function of the percentage change in both the inputs (usually labor and capital) and the stock of innovations (the technical knowledge pool). To capture the advances in knowledge, within the neoclassical growth models technology is thought of as either “augmenting” inputs, in which the rate of change in the stock of innovations is considered exogenous, or as “disembodied,” in which advancements are captured in the exogenous parameters and the error structure.

For U.S. agriculture, a few studies have examined state total factor productivity (TFP) growth rates to gain an understanding of sources of growth (e.g., see Huffman and Evenson 1993, Evenson 1996), but little systematic effort has been devoted to convergence of state TFP growth rates or to relate convergence to public and private R&D and other variables. For example, if convergence is occurring this could be related to inter-state R&D spillovers. With possibly shrinking real public resources for agricultural research, a greater understanding of spillover effects seem important to future funding decisions. For example, if there are significant interstate spillover effects of public agriculture research, then policies to encourage greater regional cooperation in research might be warranted.

Evidence of convergence may exist within the agricultural sector of the United States. Table 1 shows the TFP growth rates for the crop and livestock sectors of 42 U.S. states. The table has been partitioned by four sub-periods between 1950 and 1982. As shown, there exists differences in TFP growth rates across the states for a given time period and across the sub-periods for a given state. For example, in the Southern Plains region Oklahoma’s TFP growth rates in the crop sector vary from a high of 10.01 for 1950-60 to a low of -2.29 for 1961-70. In the Oklahoma livestock sector, growth rates range from as high as 2.65 for 1978-81 to a low of -0.34 for 1961-70. Variances in TFP growth rates can also be seen across the states. For example, in the crop sector during 1961-70, TFP growth rates vary from a high of 6.57 in Nevada to a low of -2.29 in Oklahoma. While variances in TFP growth rates provide little evidence of TFP convergence, it does offer the foundation for convergence research.

Further evidence of convergence of TFP growth rates can be seen within the agricultural sectors of the U.S. In Figure 1, for the crop, livestock and aggregate agricultural sectors, Charts 1-3 provide a plot of the annual average growth rates of TFP during 1950-82 against ℓnTFP in 1950 for 42 U.S. states and regression line from fitting the growth rate to $\ell nTFP_{50}$. As shown, the annual average growth rates of state TFP for the crop, livestock and aggregate sectors are negatively related to ℓnTFP in 1950. These charts, showing a negative relationship between average growth of TFP and initial ℓnTFP, suggest convergence, that is, those states with relatively low initial levels of TFP had a higher TFP growth rates during 1950-82 than those states with higher initial levels of TFP.

The objectives of this paper are to examine the contributions of public and private R&D to convergence in state agricultural TFP growth rates and to present implications for the organization of public agricultural research. When agricultural research activity in a given state is increased, there are two types of impacts. First, it will increase knowledge and agricultural productivity in that state (source-state effect) and tend to slow the rate of convergence in agricultural productivity across states. Second, when there are interstate knowledge spillovers due to R&D, it will also raise agricultural productivity in (some) other states and potentially narrow the productivity gap across states. Hence, the hypothesis is that an increase in agricultural

R&D in any state has effects on the rate of convergence of TFP growth that pull in opposite directions. Furthermore, the effects may differ between crop and livestock sectors.

Model

The model of convergence in state TFP growth rates is one where economic factors, e.g., public and private research, farmer's schooling, and regional effects, are hypothesized to explain differences across states. Because we are dealing with U.S. states where there is free mobility of inputs, except for land and climate, and technologies, we expect the state agricultural TFP growth rates to converge to their long-run steady state rather than to diverge. The practical implication is that those states that have relatively low agricultural TFP early experience more rapid TFP growth rates later. This is in contrast to an alternative outcome where states that experience high TFP early also have high TFP growth rates later.

Empirically, it is useful to view the tendency for convergence in TFP growth to occur over periods longer than one year, e.g., over T years. Following Barro and Sala-i-Martin (1991, 1992), we consider the following nonlinear equation representation of average TFP growth over internal T (say 5 years):

$$(1) \qquad (1/T)\ln\left(TFP_{i,t+T} / TFP_{i,t}\right) = \alpha - \left[\left(1 - e^{-\beta T}\right)/T\right] \ln\left(TFP_{i,t}\right) + \mu^{*}_{it}$$

where β is an indication of the average rate of TFP convergence for a set of states between t and t +T on the initial TFP level. μ^{*}_{it} represents a random disturbance or the effects of other non-measured factors. We assume μ^{*}_{it}'s have a zero mean, the same variance (σ^2_{μ}) for all states, and are independent over time and across states.[1] Equation (1) assumes all states have the long run steady state growth rate, α. The coefficient α is a function of the steady state TFP growth rate for the set of states and can be viewed as a function of the steady state growth rate of state agricultural output. Therefore, under the representation in equation (1), the average growth rate of TFP_i over interval T is a function of the initial level of TFP_{it}, the convergence parameter β, α and μ^{*}_{it}.

From equation (1), a key relationship for convergence is,

$$(2) \qquad d[1/T \, \ell n(TFP_{i,t+T}/TFP_{it})]/d[\ell n(TFP_{it})] = -(1-e^{-\beta T})/T$$

where $-(1-e^{-\beta T})<0$, given $0<\beta<1$. If $\beta>0$, a higher initial level of TFP_{it} implies a lower average TFP growth rates over the interval T. For a given β, as $T \rightarrow \infty$ (the interval gets large) then $-(1-e^{-\beta T})/T$ goes to 0, implying the average growth in TFP is determined by α and shocks or the disturbance term.

The agricultural sector has some unique features that affect productivity growth rates when compared to other sectors of the economy. First and foremost, the environmental or geoclimatic conditions have a direct affect on the biological activity of plants and animals. While environmental conditions do affect other sectors' production and productivity, no other sector of the economy is as sensitive to geoclimatic conditions. Environmental conditions vary geographically and play a major role in determining what plants and animal species are produced in any area.

Plants tend to be more sensitive than most animals to the geoclimatic variation, with growth phases of plants strongly affected by temperature, day-length, and soil conditions. For example, hybrid corn and soybean varieties are developed and recommended for planting in specific geoclimatic regions depending on which hybrid or variety performs the best. Other varieties are developed and recommended for planting in other areas. Because of the sensitivities to surrounding conditions, new innovations developed in one state will have a higher probability of adoption in those states or regions having similar geoclimatic conditions. Within the U.S., this tends to imply that states that are physically close to one another are more likely to have similar growing conditions than states that are a longer distance apart. This has been shown in new innovations for specific crops. For hard red winter wheat varieties, Huffman and Evenson 1993, p 170-71, have shown that a larger share of the varieties planted by farmers in U.S. major wheat producing states was developed locally or in adjacent states.[2]

The growth phases of animals are less sensitive to temperature and day-length than plants. Across the United States we see relatively little genetic variation in the dairy cows, swine, and poultry that are raised or recommended. This is especially true in the broiler industry where single breeds tend to dominate production. In beef cattle and sheep, which spend most of their life outside and obtain most of their feed from grazing, performance seems to be a little more sensitive to genetic composition (see Huffman and Evenson 1993, p. 13, 15). However, regional differences have occurred in the livestock sector but have been more evident in the compositional mix of livestock production. Within the U.S., livestock production has become specialized over time. For example, broiler production has become specialized in the Southeast. Because of the sensitivities to geoclimatic conditions along with sensitivities to production mixes, regional differences are expected in the TFP levels.

Agricultural research, both public and private, is a major source of advances in knowledge or innovations that increase productivity in agriculture. Public agricultural research in the federal government is conducted largely by the USDA's Agricultural Research Service and Economic Research Service. This research seems to have a generally national or regional focus suggesting widespread geographical benefits. Public agricultural research in the state governments is conducted by the state agricultural experiment stations and state veterinary medicine schools. Agricultural research conducted in these state institutions has as its primary goal benefitting clientele residing in the respective states and secondarily to provide spillover benefits to other states and the nation. When additional public agricultural research is undertaken in one state, we expect an increase in productivity there and this will tend to slow the rate of convergence in TFP growth rates. To the extent that there are also spillover benefits to other states, TFP growth rates in other states will increase and this would tend to cause convergence of TFP growth.

Private sector R&D is undertaken with the expectation of marketable products, processes, or biological materials which will be profitable. Two key dimensions of profitability are profit margins and total number of units marketed or size of the market (e.g., see Griliches 1957). Thus for many new private sector innovations, we expect the size of the market to be sizable, frequently extending across several states. Thus, we expect that private R&D will be a positive factor for convergence of TFP growth.

Efficient channels of technology transfer and adoption are expected to be a positive factor for convergence of TFP growth rates. Farmers' education has been shown to affect their decisions on adoption of new and profitable technologies and on information acquisition or to more generally enhance their allocative efficiency (see Huffman 1997; Wozniak 1993). Thus, we hypothesize that an increase in the average education of a state's farmers will increase the rate of TFP convergence.

Equation (3) summarizes our empirical representation of factors affecting convergence in state TFP growth rates (with i, the state identifier, suppressed to simplify):

$$(3) \qquad (1/T)\ln\left(TFP_{t+T}/TFP_t\right) =$$

$$\alpha_0 + \sum_{j=1}^{J} \alpha_j D_j - \left[\left(1 - e^{-(\beta_0+\beta_1 R_t+\beta_2 R_t^{*}+\beta_3 R_t^{p}+\beta_4 E_t)T}\right)/T\right] \ln(TFP_t) + \mu_t^{**}$$

where D_j represents the j^{th} regional dummy variable, and R_t and R_t^* represent stocks of own public agricultural research and spill-in stocks of public agricultural research, R_t^p is the stock of private agricultural research, and E_t is farmers' average schooling level. μ_t^{**} is the new disturbance term.

Equation (3) is considered conditional in that we allow for differences in the long-run steady states among regions of the U.S. These differences are captured in the α_j's when each α_j represents a different region of the U.S. (see Table 1 for the definitions of the regional dummy variables). We stay with state political boarders, rather than geoclimatic boarders, because of the importance of state governments in funding public R&D for agriculture.

In equation (3), the βs are of primary interest. β_o represents the "fixed effect" or common rate of convergence of TFP growth across all states. If an increase in a state's own public agricultural research stock (R_t) tends to slow the rate of TFP convergence, β_1 will be negative. If an increase in the public agricultural research stock from other states spills-in (R_t^*) and tends to cause an increase in the rate of convergence, then β_2 will be positive. If private agricultural research and farmers' education speed convergence, then β_3 and β_4 will be positive.

Data and Variables

The data for this study builds on earlier work by Huffman and Evenson (1993, 1994). The data are annual, 1950-82, and cover 42 U.S. states. In this data set, the New England states, Alaska, and Hawaii were excluded primarily because they accounted for a small share of total U.S. farm output (about 2% in 1974), and this share has been declining over time. In addition, Alaska and Hawaii are geographically isolated from the other 48 contiguous states, and this isolation makes spillovers of public agricultural research different than for contiguous states. Thus, our data set contains only 42 states.

The H-E data set contains state total factor productivity measures for a crop sector, livestock sector, and an aggregate agricultural sector. The TFP data were developed at Yale University, and their derivation built upon recommendations of an AAEA Task Force on Productivity Statistics (USDA 1980) and earlier work by Landau and Evenson. Our data on public and private agricultural research stocks and farmers' education are also taken from the Huffman-Evenson data set. See table 2 for more details on definitions of variables.

Results

State TFP growth rates for a crop sector, livestock sector, and aggregate agricultural sector are examined for evidence of convergence. The TFP growth rates are defined for all 5-year intervals, 1950-82. By using overlapping intervals, we avoid having to choose an arbitrary starting point as in Barro and Sala-i-Martin 1991, 1995 and Sala-i-Martin 1994. If technology transfer and adoption are occurring relatively rapidly, a five-year interval seems long enough for indications of convergence in TFP growth rates to occur. Tables 3 to 5 present maximum likelihood estimates of the parameters of equations (1) or (3), and they provide the evidence for tests of hypotheses of unconditional and conditional convergence.

Unconditional Convergence

The evidence for unconditional convergence of state agricultural TFP growth rates comes from fitting equation (1), and it provides a key benchmark for our analysis. For each sector in this scenario, all states are assumed to have the same long-run steady state, α, and the same convergence parameter, β.

In Table 3, the estimates of β for the crop sector, livestock sector, and aggregate agricultural sector are positive, implying convergence in TFP growth rates, and are significantly different from zero at the 5 percent level. The estimates of β are 0.08 for the crop sector, 0.101 for the livestock sector, and 0.102 for the aggregate agricultural sector. These results imply that the speed of convergence would be 8% per year, 10.1% per year, and 10.2% per year for the crop, livestock and aggregate agricultural sectors, respectively. Furthermore, the estimate of β is larger for the livestock sector than the crop sector, which is evidence in favor of our hypothesis that the rate of convergence in TFP growth rates in the livestock are faster than in the crop sector. The estimate of β for the aggregate agricultural sector is about the same size as for the livestock sector. This suggests that convergence in state agricultural TFP is relatively fast when adjustments are considered across the whole agricultural sector of a state.

Whether these rates of unconditional agricultural TFP convergence are judged to be large or small is somewhat subjective. Barro and Sala-i-Martin 1995 (p. 387-390) have fitted a model like equation (1) to data for per capita personal income (and per capita gross state product) of U.S. states. Their results for the period 1950-80 imply a slower rate of convergence for state per capita income, approximately 2 percent per year, than we obtained for state agricultural TFP. However, it does seem reasonable that state agricultural TFP would converge at a faster rate than state per capita income.

Using the fitted results from Table 3, the change in the TFP growth rate for a change in $\ln TFP_t$ can be calculated using equation (2). For the crop, livestock, and aggregate agricultural sectors, a one percent increase in $\ln TFP_t$ results in slowing the TFP growth rate by 6.6, 7.9, and

8.0 percent, respectively. These results suggest that within the U.S. agricultural sector, states with lower productivity levels tend to have higher rates of TFP growth than those states with higher productivity levels. This seems reasonable in an open economy such as in the United States, with technology, along with inputs, migrating towards areas of higher rates of return.

Conditional Convergence

We attempt to learn more about convergence in agricultural TFP growth rates by first introducing regional fixed effects and then augmenting them with research stocks and farmers' schooling. Because we are ultimately concerned about implications for state and national funding decisions on public agricultural research, we adopt the regional grouping of states used by Khanna, Huffman, and Sandler 1994 (see Table 1). This latter study focused on state government decisions on expenditures for agricultural research.[3]

Regional Fixed Effects. The hypothesis to be tested is that there are common but unspecified regional effects on the long-run steady state properties of TFP growth as reflected in ". The parameter estimates from fitting equation (3) including regional effects, but excluding R_t, $R_t^{(}$, and E_t, are reported in Table 4. The Pacific region is the excluded region and reference region, so the coefficients of the regional dummy variables provide estimates of difference relative to the Pacific region.

The coefficients of all the regional dummy variables in the three TFP convergence equations are significantly different from zero at the 5 percent level, except for one.[4] For the crop sector and aggregate agricultural sector equations, the coefficients of all regional dummy variables are negative implying that the Pacific region has a long-run steady state agricultural TFP growth rate for these sectors that is higher than for the other regions. For the livestock sector equation, the coefficients of regional dummy variables are positive, except for the Mountain region. These positive coefficients imply higher rates of long-run steady state livestock TFP growth outside the Pacific region.[5]

After controlling for regional fixed effects on α, the estimate of the convergence parameter β is larger than those reported in Table 3; 0.118 vs. 0.08 for the crop sector, 0.138 vs. 0.101 for the livestock sector, and 0.146 vs. 0.102 for the aggregate sector. The estimates of the convergence parameter β imply that the speed of convergence would be 11.8% per year, 13.8% per year, and 10.1% per year for the crop, livestock and aggregate agricultural sectors, respectively. Thus, moving from a model of unconditional convergence of TFP growth to a model of regional fixed effects results in higher rates of implied agricultural TFP convergence. This seems consistent with significant interregional differences in climate, soils, public agricultural research activity, and other things that can be expected to affect the level of agricultural TFP growth rates.

Using equation (2), the change in TFP growth rate given an increase in $\ln TFP_t$ can be calculated. For the regional fixed effects model, the estimated marginal effects of a change in $\ln TFP_t$ are greater than those reported in the unconditional model; -8.9 vs. -6.6 percent for the crop sector, -10.0 vs. -7.9 percent for the livestock sector, and -10.4 vs. -8.0 percent for the aggregate agricultural sector. These results again imply an increase in $\ln TFP_t$ slows the rate of growth in TFP. The results continue (even after controlling for different long run steady states) to suggest that states with lower TFP levels will tend to have higher rates of TFP growth.

A Full Set of Factors. The hypothesis to be tested here is that the speed of convergence, after controlling for regional differences in the steady state, is a function of state public and private research stocks and farmers' schooling. Public research stocks are separated into three components using a national map of agricultural geoclimatic regions and subregions (see Figure 2, and Huffman and Evenson 1993, p. 195). For each state, there is an "own" research stock variable (RS_t) and two "spill-in" research stock variables. One spill-in research stock variable is for the stock of research performed outside the state of interest but in similar subregions of adjacent states ($RSS_t^{(}$). The other spill-in research stock variable is for the stock of research performed outside the state of interest and similar subregions of adjacent states but otherwise within the same geoclimatic region(s) as the observation state ($RSR_t^{(}$). If public agricultural research is an impure public good, we expect $RSS_t^{(}$ to have a larger impact on convergence of TFP growth rates than $RSR_t^{(}$ because $RSS_t^{(}$ should be a better technological match. These research stock variables are from Huffman and Evenson (1993).

The maximum likelihood estimates of the parameters in equation (3) for the crop sector, livestock sector, and aggregate agricultural sector are reported in table 5. The results show that a states own investment in public agricultural research slows the rate of convergence of agricultural TFP growth rates. In the crop sector, the coefficient of "own" public crop research stock is negative and significantly different from zero at the 5 percent level. In the livestock sector, the coefficient of "own" public livestock research is also negative and significantly different from zero at the 5 percent level. On the other hand, larger public agricultural research "spill-in" variables increase the speed of convergence of agricultural TFP growth rates. In the crop sector, the coefficients of the public crop research spill-in variables are positive and significantly different from zero. Furthermore, as expected, the coefficient for the similar subregion spill-in research stock variable is larger than for the coefficient of the similar region research stock variable. For the livestock sector, the spill-in research stock variables for similar subregions is positive and significantly different from zero at the 5 percent level. The coefficient of the spill-in similar region research stock variable, however, is negative and significantly different from zero. This is somewhat surprising because our expectation is for positive spill-in effects and for more prevalent research spillovers for livestock than crop research.

Private agricultural stocks tend to speed convergence of TFP growth rates in both the crop and livestock sectors. The coefficient of the stock of private crop research is positive but not significantly different from zero in the crop sector growth equation. The coefficient of private livestock research is positive and significantly different from zero in the livestock sector growth equation. These results are consistent with R&D in the private sector developing new crop and livestock technologies that have at least a regional market.

Farmers' education increases the speed of convergence of TFP growth rates. The coefficient of farmers' education in the crop and livestock sector TFP growth equations is positive and significantly different from zero at the 5 percent level. This finding is consistent with farmers' education enhancing their ability to acquire information and adopt profitable new technologies.

The joint null hypothesis that the convergence parameter β does not depend on public and private R&D stocks and farmers' schooling is rejected at the 5% significant level. The sample value of the χ^2 for the crop, livestock and aggregate sector is 354, 372, and 504, respectively, and the critical values are 11.07, 11.07, and 16.92 with 5, 5, and 9 degrees of freedom, respectively.

Using the sample means for the public and private research variables and farmers schooling and applying their respective estimated β coefficients, the speed of convergence is calculated. The implied $\hat{\beta}$'s for the crop, livestock and aggregate agricultural sectors are 0.085, 0.102 and 0.086, respectively. Thus, the results imply an 8.5%, 10.2%, and 8.6% per year rate of convergence to a steady state. Using equation (2) and the estimated $\hat{\beta}$'s, the change in average rate of TFP growth given a percentage increase in $\ell n TFP_t$, or marginal effect of a change in

RnTFP_t, are -6.9, -8.0 and -7.0 percent, respectively. For the full effects model, the crop sector and livestock sector results, evaluated at the sample mean, are more in line with the estimated results for the benchmark model using equation (1) than with those reported in Table 4. The aggregate agricultural sector estimates speed of convergence and marginal effect were lower relative to the both the unconditional model and the regional fixed effects model. However, the results continue to imply that lower initial levels of TFP lead to higher future rates of TFP growth.

An alternative representation of agricultural research spill-in effects is one where research conducted in any state is equally likely to spill-in to any other state. The idea is that "own" state research is different from other states' research, but research conducted in any other state is equally likely to spill-in. Note this does not imply that other states' agricultural research spills-in perfectly. Our data are such that we perform this experiment for both public and private agricultural research. The results from this experiment are reported in Appendix B.

The results, which are reported in Appendix B, Table 1B, do not in general support this alternative representation of agricultural research spill-in effects. In the crop and livestock productivity equations, the coefficients of the broad based public and private agricultural research variables are not significantly different from zero at the 5 percent level. Hence, we judge the results in Table 5 to be the best overall representation of state agricultural TFP convergence.

Conclusion

This paper has presented evidence for the United States that state TFP growth rates tend to converge in both the crop and livestock sectors, and the rate of convergence is faster for the livestock than the crop sector. This suggests that higher levels of TFP at any date tend to lead to slowing subsequent agricultural TFP growth rate. The results also suggest that regional differences exist in the long-run steady state of agricultural TFP growth rates. These differences seem most likely due to underlying regional differences in climate, soils, public agricultural research activity, and fixed factors. Our finding of econometric evidence in favor of state agricultural TFP growth convergence and that the rate is positively related to our empirical measures of public agricultural research spill-ins supports the hypothesis of significant interstate public agricultural research spillover effects.

Our results also showed that the convergence parameter is unlikely to be a constant across states, and most likely to be variable depending on own and spill-in public agricultural research stocks, private agricultural research stocks, and farmers' schooling. These are the same variables that have been shown to play an important role in explaining variations in levels of state agricultural TFP by Huffman and Evenson (1993) and others. In this study, the investment in agricultural research by any given state is shown to have two opposite effects on agricultural TFP convergence. First, its direct effect within the state where it is undertaken is to slow convergence in both the crop and livestock sectors. Second, its indirect effect through interstate spillover effects on the agricultural TFP growth rate of other states is to increase the rate of agricultural TFP convergence. These results support other studies that have found that public agricultural research in the U.S. states produces impure public goods.

Our results have important implications for inter-regional competition and research planning. The local private good component of public agricultural research gives local producers a competitive advantage against farmers in other states. The spillover effects of public agricultural research are best described as regional rather than national. Public agricultural research undertaking in a given state is more likely to have spillover effects in a state that is in close proximity to it than to spillover equally across all U.S. states. This means that farmers in surrounding states can expect to obtain some but not full benefits of the agricultural research conducted in a given state, but farmers in distant states are expected to receive little or no benefit.

With significant public agricultural research spillover effects, independent state planning of agricultural research is socially inefficient. Also, because of the significant regional, as opposed to national, nature of public agricultural research spillovers, we suggest that rigid national planning of public agricultural research is also inefficient. A better organizational structure would be the establishment of stronger incentives for cooperation and new political jurisdictions for financing public agricultural research that has interstate spillover effects across states. Furthermore, it seems that interstate cooperation for crop and livestock research might look quite differently. For example, only a few excellent programs in poultry, dairy, and swine research seem likely to be needed so a large number of states should work together. But for wheat, corn, and soybean research more centers of excellence are needed and fewer states should work together. Furthermore, we do not see the current regional research grouping of states providing the optimal grouping for efficient financing of the impure public goods created by public crop and livestock research.

Footnotes

[1] The random disturbance term, μ^{*}_{it}, can be represented as the average of two annual error terms, $\mu^{*}_{i1} = 1/5(\mu_{i6} - \mu_{i1})$, $\mu^{*}_{i2} = 1/5(\mu_{i7} - \mu_{i2})$, etc., where μ_{it}'s are disturbances in an annual relationship. See Appendix A for a more extensive discussion of the error structure used in this model.

[2] International transfers of wheat and rice varieties also occur, e.g. see Byerlee and Traxler 1996, Evenson and Gollin 1997, and Pardey et al. 1996.

[3] The regional groupings follow state political borders rather than geoclimatic borders. The reason to use political rather than geoclimatic borders stems from our focus on governmental funding, which is currently based on political borders.

[4] The null hypothesis that the coefficients of the regional dummy variables are jointly zero is rejected at the 5% significant level. The sample value of the χ^2 for the crop, livestock and aggregate sector is 178, 200, and 196, respectively, and the critical value is 12.59 with 6 degrees of freedom. The conclusion is that regional differences in the long-run steady state of TFP growth rates do exist.

[5] However, to the extent that there are important variables for explaining cross-state variation in convergence that are excluded from the regressions but are correlated with the regional dummy variables, the estimated coefficients of the dummy variables will be biased (Greene 1997, pp. 402-4).

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Table 1. Annual crop and livestock MFP growth rates by state and region for selected periods.

	Crop Production MFP				Livestock Production MFP			
State/Region	1950–60	1961–70	1971–77	1978–82	1950–60	1961–70	1971–77	1978–82
Northeast								
New York	.21	2.37	-3.40	-1.01	1.42	1.27	.35	3.44
New Jersey	.91	2.12	-4.63	-.49	1.80	1.83	-2.31	4.69
Pennsylvania	2.68	3.28	-.15	.43	2.40	1.35	2.73	4.24
Delaware	2.82	.07	-2.65	3.47	3.71	3.00	4.79	2.90
Maryland	1.36	1.85	-3.22	4.95	2.50	2.13	2.60	1.97
Region Total	1.10	1.95	-2.87	-.35	2.04	1.56	1.65	3.64
Lake States								
Michigan	2.59	2.75	3.46	3.02	.82	2.03	4.19	1.10
Minnesota	4.76	2.20	4.84	.60	1.14	.97	2.21	-.12
Wisconsin	.41	3.65	4.02	-2.31	2.05	1.83	1.37	1.20
Region Total	2.87	2.19	3.81	-.47	1.50	1.49	2.23	.62
Corn Belt								
Ohio	2.83	2.25	1.09	1.73	1.49	2.04	-.88	3.59
Indiana	3.62	1.61	1.38	3.94	1.03	1.37	-1.50	3.76
Illinois	3.81	.38	2.92	2.19	1.20	-.04	-1.51	1.56
Iowa	3.43	2.05	.90	3.75	-.04	.30	.37	-.97
Missouri	3.52	.44	4.83	1.27	1.27	1.21	2.96	-.11
Region Total	3.33	1.06	1.75	2.02	.84	.75	-.03	.58
Northern Plains								
North Dakota	1.28	2.03	2.53	5.27	3.03	-.04	2.22	-1.02
South Dakota	3.93	-.48	3.91	3.74	2.26	.52	1.49	-2.13
Nebraska	2.79	.75	3.61	1.45	1.17	1.01	-.75	-.33
Kansas	5.01	-.14	1.89	.56	1.78	1.76	-.90	1.80
Region Total	3.47	.29	2.67	1.88	1.82	.89	-.07	-.13
Appalachia								
Virginia	1.62	2.51	-1.08	2.02	2.90	2.32	3.80	1.23
West Virginia	1.27	.48	-1.64	9.14	3.60	2.32	3.22	4.95
Kentucky	1.26	2.45	4.26	3.09	3.39	2.99	-.07	10.02
North Carolina	3.61	3.32	-.30	2.63	4.81	3.06	2.02	3.14
Tennessee	2.45	1.30	3.38	4.82	2.46	2.02	1.47	3.71
Region Total	2.47	2.31	.96	2.62	3.46	2.74	1.76	4.89
Southeast								
South Carolina	3.95	3.04	1.54	4.38	5.03	2.79	.28	5.11
Georgia	4.09	3.50	-3.09	7.42	3.72	.99	.52	3.10
Florida	.14	2.44	1.68	-.38	1.53	-1.88	3.51	-.33
Alabama	4.87	1.81	1.91	6.40	5.67	1.00	2.30	1.91
Region Total	3.46	3.13	.27	2.82	3.83	.62	1.70	2.21
Delta States								
Mississippi	5.51	4.50	1.93	2.82	5.68	1.94	3.23	3.53
Arkansas	5.67	2.96	1.99	.04	4.46	1.77	3.84	4.98
Louisiana	3.29	4.72	1.45	1.02	2.21	2.32	3.05	4.34
Region Total	5.03	3.63	1.42	.82	4.07	1.88	3.46	4.49
Southern Plains								
Oklahoma	10.01	-2.29	4.43	.49	2.24	-.34	1.25	2.65
Texas	5.49	.76	4.36	-5.39	1.65	-.25	.24	.15
Region Total	6.39	-.04	3.83	-4.26	1.64	-.36	.53	.74
Mountain States								
Montana	-1.66	2.18	.69	1.24	4.20	-.18	.13	.65
Idaho	-.94	4.49	-1.69	2.55	2.11	.37	.36	2.61
Wyoming	-1.05	5.40	-1.10	.14	2.20	.26	.98	-.32
Colorado	4.21	.57	.30	2.53	1.31	.05	1.48	2.88
New Mexico	5.03	2.05	2.69	-1.38	.96	-.70	-1.71	4.39
Arizona	1.11	1.12	3.82	-3.65	-2.04	.72	-.99	-1.71
Utah	-2.53	2.64	-.50	-2.30	2.27	.03	1.86	.12
Nevada	-1.04	6.57	3.09	-.98	-2.54	-.12	.64	.17
Region Total	.96	1.76	.58	.10	1.45	-.08	.26	1.38
Pacific States								
Washington	-1.10	3.52	1.90	2.29	3.17	.60	2.98	2.72
Oregon	1.41	3.01	2.10	1.00	2.20	1.46	.03	2.27
California	2.45	2.68	3.35	-1.51	.47	.50	.33	2.01
Region Total	1.75	2.49	2.84	-1.01	1.27	.60	.74	2.16

Source: Huffman and Evenson 1993, p. 200.

Table 2. Definitions of regressors.

Regions	
Central[1]	Indiana, Illinois, Iowa, Michigan, Missouri, Minnesota, Ohio, Wisconsin
Northern Plains	Kansas, Nebraska, North Dakota, South Dakota
Mountain	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming
Southern Plains	Arkansas, Louisiana, Mississippi, Oklahoma, Texas
Southeast	Alabama, Florida, Georgia, Kentucky, North Carolina, South Carolina, Tennessee, Virginia, West Virginia
Northeast	Delaware, Maryland, New Jersey, New York, Pennsylvania
RC_t[2]	Crop sector, state public commodity-oriented research stock constructed using commodity share weights and a time-lag pattern over 33 years of (7,6,20).
RL_t	Livestock sector, state public commodity-oriented research stock constructed using commodity share weights and a time-lag pattern over 33 years of (7,6,20).
$RSSC_t^($	Crop sector, similar sub-region, state public commodity-oriented research stock of spill-in crop research from other states in similar geoclimatic sub-region.
$RSRC_t^($	Crop sector, similar region, state public commodity-oriented research stock of spill-in crop research from other states in similar geoclimatic region excluding $RSSC_t$.
$RSSL_t^($	Livestock sector, similar sub-region, state public commodity-oriented research stock of spill-in livestock research from other states in similar geoclimatic sub-region.
$RSRL_t^($	Livestock sector, similar region, state public commodity-oriented research stock of spill-in livestock research from other states in similar geoclimatic region excluding $RSSL_t$.
RC_t^P	Crop Sector, state private agricultural research stock constructed using commodity revenue weights and a time-lag pattern over 33 years of (7,6,20).
RL_t^P	Livestock Sector, state private agricultural research stock constructed using commodity revenue weights and a time-lag pattern over 33 years of (7,6,20).
E_t	State average number of years of schooling completed by rural farm males 25 years of age and older (U.S. Dept. of Commerce, *Census of Population*)

[1] The pacific region dummy is excluded. States included are California, Oregon, Washington.

[2] See Huffman and Evenson, 1994, for explanation of variables used.

Table 3. Parameter estimate of crop, livestock, and aggregate sector TFP growth equations: 5 year overlapping state averages, 1950-1982 (t-values in parentheses).[1]

Parameters	Crop sector	Livestock sector	Aggregate sector
"	0.014	0.018	0.019
	(7.25)	(11.14)	(11.66)
$	0.080	0.101	0.102
	(13.32)	(14.18)	(14.19)
R^2	0.163	0.198	0.199

[1] Dependent variable is $\ln(TFP_{t+5}/TFP_t)$. See equation (1).

Table 4. Parameter estimates of crop, livestock, and aggregate sector TFP growth equations: 5 year overlapping state averages, 1950-1982, with regional fixed effects (t-values in parentheses).[1]

Variables	Parameters	Crop sector	Livestock sector	Aggregate sector
Intercept	"$_0$	0.075	0.013	0.058
		(11.05)	(2.85)	(11.81)
D_1(Central)[2]	"$_1$	-0.031	0.004	-0.023
		(4.22)	(0.81)	(4.31)
D_2(N. Plains)	"$_2$	-0.057	0.016	-0.029
		(6.76)	(2.71)	(4.79)
D_3(Mountain)	"$_3$	-0.091	-0.022	-0.066
		(11.72)	(4.29)	(11.87)
D_4(S. Plains)	"$_4$	-0.056	0.032	-0.029
		(6.89)	(5.66)	(5.05)
D_5(Southeast)	"$_5$	-0.069	0.021	-0.039
		(9.02)	(4.01)	(7.38)
D_6(Northeast)	"$_6$	-0.044	0.028	-0.016
		(5.53)	(4.90)	(2.88)
	$	0.118	0.138	0.146
		(15.72)	(16.16)	(16.09)
R^2		0.264	0.306	0.305

[1] Dependent variable is $\ln(TFP_{t+5}/TFP_t)$.
[2] The Pacific region dummy is excluded.

Table 5. Parameter estimates of crop, livestock, and aggregate TFP growth equations: 5 year overlapping state averages, 1950-1982, with a full set of factors (t-values in parentheses).[1]

Variables	Parameters	Crop sector	Livestock sector	Aggregate sector
Intercept	α_0	0.038	0.016	0.027
		(4.97)	(4.03)	(4.61)
D_1(Central)[2]	α_1	0.008	-0.005	0.003
		(1.01)	(1.12)	(0.52)
D_2(N. Plains)	α_2	-0.018	0.012	0.001
		(2.08)	(2.33)	(0.18)
D_3(Mountain)	α_3	-0.050	-0.020	-0.033
		(5.77)	(4.30)	(5.39)
D_4(S. Plains)	α_4	-0.020	0.003	-0.014
		(2.24)	(0.56)	(2.20)
D_5(Southeast)	α_5	-0.029	0.006	-0.010
		(3.61)	(1.23)	(1.57)
D_6(Northeast)	α_6	0.011	0.018	0.004
		(1.30)	(3.49)	(0.68)
	β_0	-0.452	0.581	0.065
		(5.06)	(5.15)	(0.39)
RC_t	β_1^C	-0.059		-0.038
		(9.82)		(5.82)
RL_t	β_1^L		-0.068	-0.053
			(9.37)	(7.03)
$RSSC_t^\gamma$	β_2^C	0.046		0.004
		(5.81)		(0.57)
$RSRC_t^\gamma$	β_{22}^C	0.027		0.028
		(4.82)		(4.25)
$RSSL_t^\gamma$	β_2^L		0.002	0.002
			(2.17)	(2.53)
$RSRL_t^\gamma$	β_{22}^L		-0.010	0.003
			(2.13)	(0.46)
RC_t^P	β_3^C	0.011		0.189
		(0.68)		(4.71)
RL_t^P	β_3^L		0.036	-0.114
			(3.51)	(3.32)
E_t	β_4	0.025	0.047	0.010
		(4.25)	(9.17)	(1.56)
R^2		0.431	0.470	0.517
$\hat{\beta}$[3]		0.085	0.102	0.086

[1] Dependent variable is $\ln(TFP_{t+5}/TFP_t)$. See equation (3).
[2] The pacific region dummy is excluded.
[3] Calculated using the sample means.

Figure 1.

Chart 1: TFP Growth Versus Initial Levels of TFP
Crop Sector

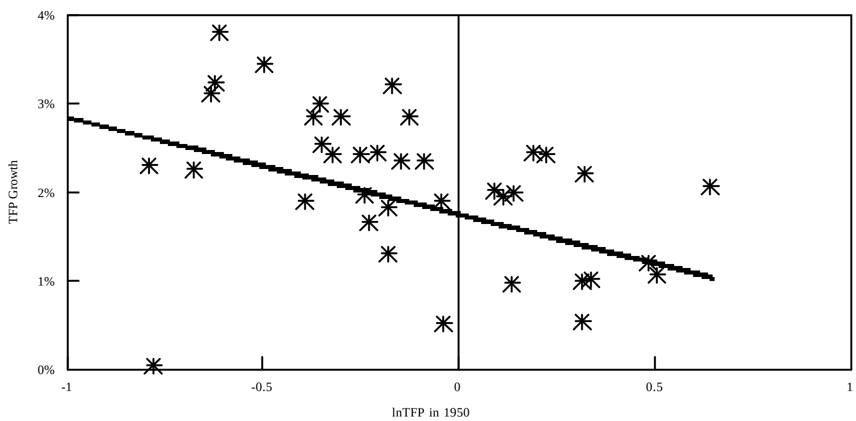

Chart 2: TFP Growth Versus Initial Levels of TFP
Livestock Sector

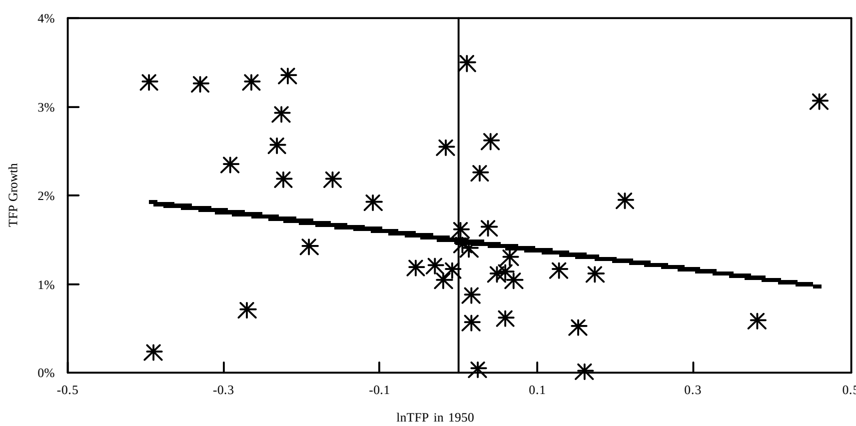

Chart 3: TFP Growth Versus Initial Levels of TFP
Aggregate Agricultural Sector

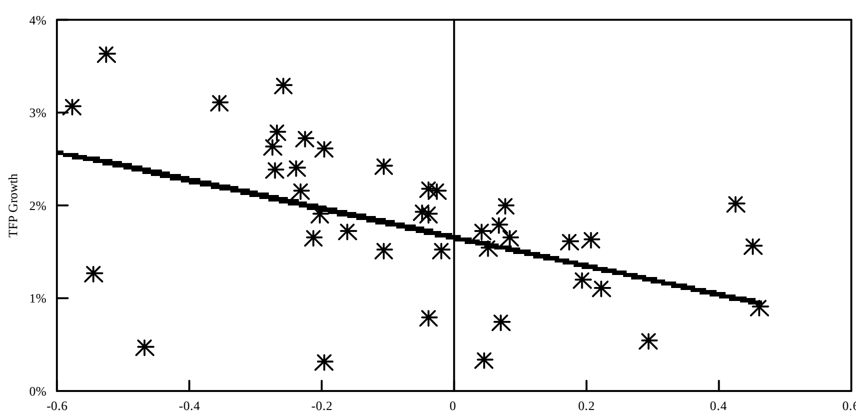

Figure 2. U.S. agricultural geo-climatic regions and subregions.

Source: Huffman and Evenson, 1993.

Appendix A.

Because the model is estimated using cross-sectional time series data, we elaborate on the potential for autocorrelated errors. The model estimated using equations (1) and (3) appear to have i.i.d. errors. By using a very simple model suggested by Carriquiry, we can show that autocorrelated errors can be handled using the systematic portion of the model and that it may not be necessary to explicity control for autocorrelated errors. For example, consider a model where $(y_t - y_{t-5})$ is regressed on y_{t-5}. Let μ_t represent an AR(1) process where

(A1) $$u_t = \rho u_{t-1} + \varepsilon_t ; \quad \varepsilon_t \sim \text{i.i.d.}(0, \sigma^2_\varepsilon) \ .$$

Next, let y_t be a function of a constant mean, μ, and u_t or

(A2) $$y_t = \mu + u_t \ ,$$

where u_t follows (A1). We can then take the one period lag and solve for μ_t or

(A3) $$\begin{aligned} y_{t-1} &= \mu + u_{t-1} \ , \\ \rho y_{t-1} &= \rho\mu + \rho u_{t-1} \ , \\ &= \rho y_{t-1} - \rho\alpha - \rho\beta y_{t-6} + \varepsilon_t \ , \\ u_t &= \rho y_{t-1} - \rho\mu + \varepsilon_t \ , \end{aligned}$$

ending with autocorrelation in the mean portion of the model and i.i.d. errors, ε_t. Substituting the results from (A3) into (A2) we get

(A4) $$\begin{aligned} y_t &= (1-\rho)\mu + \rho y_{t-1} + \varepsilon_t \ , \\ &= \alpha + \rho y_{t-1} + \varepsilon_t \ ; \quad \varepsilon \sim \text{i.i.d.}(0, \sigma^2_\varepsilon) \ , \end{aligned}$$

We can now return to the original problem where $(y_t - y_{t-5})$ is regressed on y_{t-5}. Subtracting y_{t-5} from both sides using the form solved for above we get

(A5) $$\begin{aligned} (y_t - y_{t-5}) &= \alpha + \rho y_{t-6} + \varepsilon_t - \alpha - \rho y_{t-1} - \varepsilon_{t-5} \ , \\ &= \rho(y_{t-1} - y_{t-6}) + \varepsilon^*_t \ , \end{aligned}$$

ending with i.i.d errors, ε_t*.

Appendix B.

Table 1B. Parameter estimates of crop, livestock, and aggregate TFP growth equations: 5 year overlapping state averages, 1950-1982, with broad spill-in variables (t-values in parentheses).[1]

Variables	Parameters	Crop sector	Livestock sector	Aggregate sector
Intercept	"$_0$	0.044	0.017	0.034
		(5.74)	(4.19)	(6.43)
D_1(Central)[2]	"$_1$	-0.003	-0.004	-0.010
		(0.41)	(0.84)	(1.87)
D_2(N. Plains)	"$_2$	-0.022	0.014	-0.005
		(2.45)	(2.67)	(0.86)
D_3(Mountain)	"$_3$	-0.059	-0.022	-0.040
		(6.91)	(4.65)	(7.16)
D_4(S. Plains)	"$_4$	-0.024	0.008	-0.016
		(2.69)	(1.43)	(2.74)
D_5(Southeast)	"$_5$	-0.037	0.004	-0.018
		(4.53)	(0.89)	(3.08)
D_6(Northeast)	"$_6$	-0.015	0.016	-0.003
		(1.72)	(3.23)	(0.56)
	$\$_0$	-0.003	0.065	0.307
		(0.02)	(0.35)	(1.41)
RC_t	$\$_1^C$	-0.043		-0.029
		(8.70)		(5.75)
RL_t	$\$_1^L$		-0.067	-0.052
			(9.40)	(7.14)
$RC_t^{(}$	$\$_2^C$	-0.001		0.077
		(0.06)		(3.63)
$RL_t^{(}$	$\$_2^L$		-0.012	0.001
			(0.83)	(0.01)
RC_t^P	$\$_3^C$	0.076		0.258
		(5.59)		(8.16)
RL_t^P	$\$_3^L$		0.040	-0.157
			(3.88)	(6.23)
E_t	$\$_4$	0.017	0.037	0.012
		(2.77)	(6.94)	(2.20)
$RC_t^{P(}$	$\$_3^C$	-0.001		-0.088
		(0.05)		(3.57)
$RL_t^{P(}$	$\$_5^L$		0.026	-0.010
			(1.75)	(0.06)
R^2		0.411	0.472	0.523

[1] Dependent variable is $\ln(TFP_{t+5}/TFP_t)$. See equation (3).
[2] The pacific region dummy is excluded.